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Attention: NsG-14-59-Supplement II (Work on Descent Trajectory under Supplement I has been reported separately.)

Subject: Semi-annual Status Report on Control of Nuclear Rocket.

Gentlemen:

The following material is submitted for the first Semi-annual Status Report on the work of Research Grant No. NsG-14-59-Supplement II covering the period 1, July 1963 through 31, December 1963.

Papers prepared under this period are:

(1) "Adaptive Control for Nuclear Reactor Start-up and Regulation", presented at the Ninth Annual Meeting of the American Nuclear Society, June 1963, at Salt Lake City (with F. Haag). Transaction of American Nuclear Society, Volume 6, number 1. June 1963, pp. 109-110.

(2) "Application of Optimum Control to Nuclear Reactor Start-up", to be published in the Transactions in Nuclear Science, IEEE, April 1964 (with F. Haag).

Very truly yours,

C. N. Shen

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UNPUBLISHED PRELIMINARY DATA

t: ADAPTIVE CONTROL FOR NUCLEAR

REACTOR START-UP AND REGULATION First Semi-annual Status Report, July 1 - Dec. 31, 1963

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F.G. Haag
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at the 9th Ann. meeting of the Am. Nucl. Soc., Jun. 1963 Submitted for publication

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Optimization methods[1] have been used to synthesize a reactor control system which is input adaptive[2]. The final optimized control system has several features which make it superior to conventional feedback systems. The optimization procedure defines in precise mathematical terms the purpose of the control system. The usual power overshoot, as was inherent for example in Kagayama's system[3], is eliminated. The optimum system requires amplifiers with time varying gains.

The one delay group kinetics equations[4] may be written in the form,

$$\dot{q} = m \tag{1}$$

where by definition,

$$q = \frac{1}{\lambda} \ln\left[\frac{(1-\rho)\, m}{(1-\rho_o)\, m_o}\right] \quad \text{and} \quad m = \frac{\rho}{1-\rho} \tag{2}$$

such that ρ_o and m_o are reference values of the reactivity ρ and neutron power m respectively. In the derivation of Equation (1) it has been assumed that the dynamics depend entirely on the rate of change of precursor concentration.

The input adaptive control system is found by minimizing the error criterion,

$$e(t) = \int_t^{T_2} \left\{ \lambda_1 \left[Q(\sigma) - q(\sigma)\right]^2 + \lambda_2 \left[M(\sigma) - m(\sigma)\right]^2 \right\} d\sigma \tag{3}$$

where Q and M are the desired values of q and m respectively, λ_1 and λ_2 are weighting factors and σ is future time such that $t \leq \sigma \leq T_2$, where t is the present time from which control proceeds and T_2 is the time that the control is to terminate.

By application of either dynamic programming or calculus of variations[1], the condition for the vanishing of the variation of Equation (3) is the Euler equation,

$$\frac{\partial I}{\partial q^*} - \frac{d}{d\sigma}\left(\frac{\partial I}{\partial \dot{q}^*}\right) = 0 \tag{4}$$

where I denotes the integrand of Equation (3) and the asterisk denotes the optimum control.

A desired program of constant period for T_1 time units followed by constant power operation until T_2 is,

$$
\begin{array}{lcc}
 & 0 \leq \sigma \leq T_1 & T_1 \leq \sigma \leq T_2 \\
Q(\sigma) = & \alpha \sigma & \alpha T_1 \\
M(\sigma) = & \alpha & 0
\end{array}
$$

For $t < T_1$, Equation (4) has the solution

$$m^* = (Q - q^*)\,\omega \tanh[\omega(T_2 - t)] + \alpha \left\{ 1 - \frac{\operatorname{sech}[\omega(T_2 - t)]}{\operatorname{sech}[\omega(T_2 - T_1)]} \right\} \qquad (5)$$

and for $T_1 \leq t \leq T_2$

$$m^* = (Q - q^*)\,\omega \tanh[\omega(T_2 - t)] \qquad (6)$$

where $\omega = (\lambda_1 / \lambda_2)^{1/2}$.

The complete diagram for the optimum control system, based on Equations (5) and (6), is shown on Figure 1. The corrective feedback occurs at every instant of present time. The control will be optimum in the sense of minimizing the error criterion for future time independently of how much the present output is affected by extraneous causes (noise, change in reactor constants, etc.). The system shown on Figure 1 exhibits no power overshoot.

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1 R. Bellman "Adaptive Control Processes: A Guided Tour" Princeton Un: Press (1961).

2 J.A. Aseltine et al. "A Survey of Adaptive Control Systems" I.R.E. Trans. on Automatic Control <u>6</u> 102 (1958).

3 T. Kagayama, "Dynamic Analysis of Start-up of a Nuclear Reactor" Proceedings of the Second U.N. International Conference on the Peaceful Uses of Atomic Energy, Vol. 11 Reactor Safety and Control, Geneva, 1948.

4 M.A. Schültz "Control of Nuclear Reactors and Power Plants" second edition, McGraw-Hill (1961).

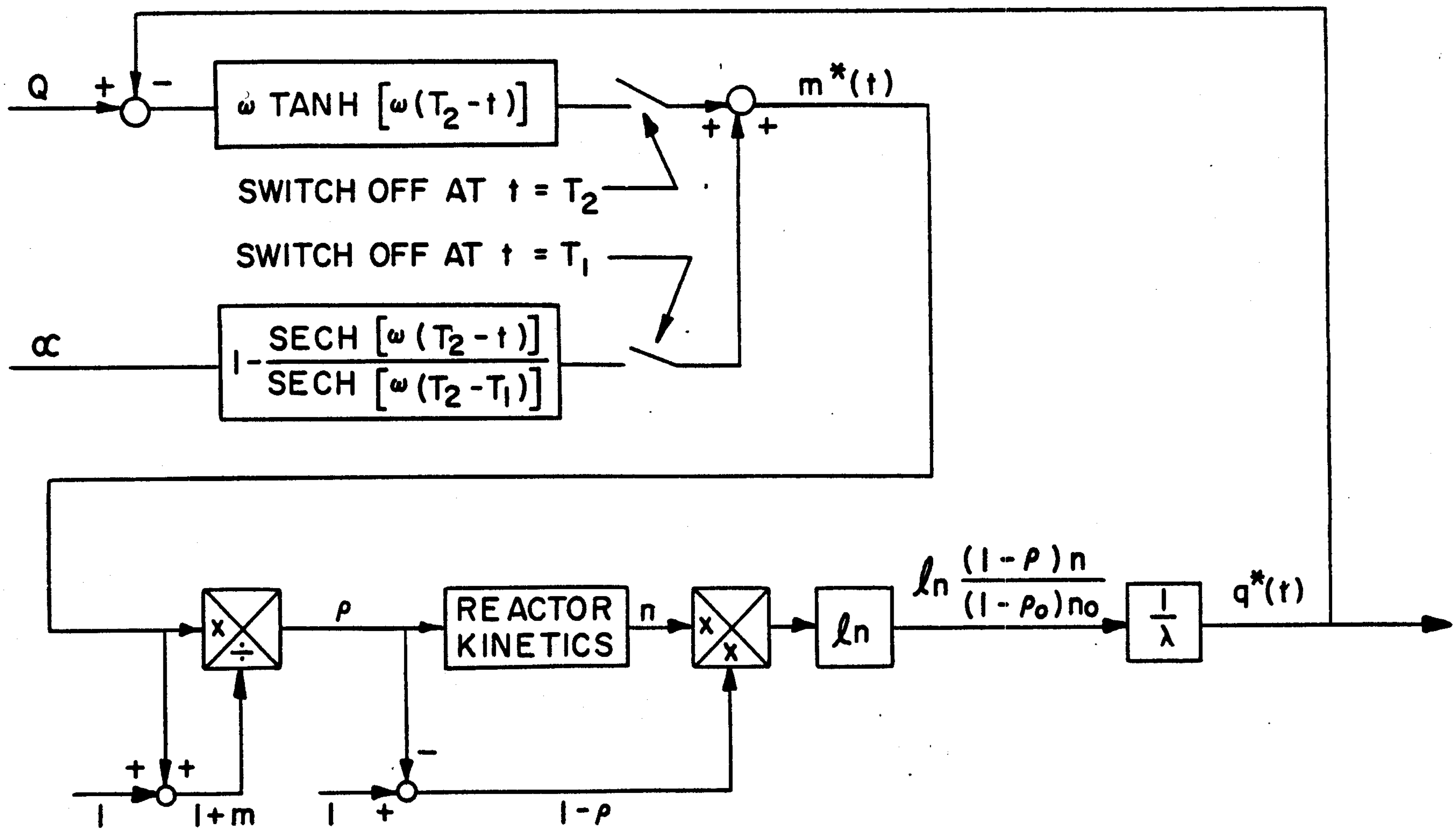

FIGURE I. OPTIMUM COMPUTER CONTROL FOR START-UP

C.N. SHEN/F.G. HAAG

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